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Review on multi-input DC-DC converters topologies for electric vehicle charging application

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ABSTRACT

The evolving fast-charging technology ends the hindrances of electric vehicle (EV) usage by integrating renewable energy sources and hybrid energy storage systems to increase the range and reliability of the vehicle. Nowadays, the development of the smart grid hosts bi-directional operation for improving the power quality by sending power from EV to the grid. For that, the multi-input (MI) converters are the breakthrough with the bidirectional conduction operation, which supports the power flow from vehicle to grid, vehicle, and building operation (V2X). Another important criterion for EV chargers is the high-power density with less losses by zero voltage and current switching and less circulating current, which can be achieved with resonant converters. All existing reviews missed out on focusing on resonant converters for bi-directional MI converters. This paper reviews the bi-directional converter topologies with multiple inputs suitable for V2X operation based on high and low voltage, frequency, control, and switching components.

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1. INTRODUCTION

The primary cause of global warming and most ecological issues is pollution due to transportation, where the emission of heat and greenhouse gases are dispersed to the environment, causing air adulteration. The ruin of fossil fuel turns out towards the renewable energy sources or RES to guard our environment against the affluence of global environmental disasters [1]. This peculiar nature made the environmentalists promote electric vehicles (EVs) through great awareness and developing better policies to give subsidies based on the standards. When the EV is charging using a grid, it again increases the demand for fossil fuels, which indirectly does not satisfy the desire [2]. The far-fetched factor of the integration of RES, which limits its application, is the dynamics, low voltage, and discrepancy in nature [3]. Each of them needs a powerful electronic interface to provide a reliable output and better control to get the desired result. Transportation electrification is a great solution to reduce the carbon footprint when it is integrated with RES for charging.

The fore of the EV focuses on its better performance in speed, range, and charging time with less cost compared to an internal combustion engine to increase the utilization of EV. The panacea for the downsides of EVs is incorporating multiple sources in the input like solar, wind, fuel cell, supercapacitor, and battery to empower the EV power and energy to meet the range and speed [4]. Then, the power management between the sources becomes a great challenge to obtain the optimum energy utilization. Depending on the output of the RES, the power electronic interface has been chosen with a separate controller for better control, which significantly increases the size and weight, directly incurring high costs [5]. Conventional converters have a single input and single output until renewable energy sources and energy storage devices play a major role in meeting the load demand with high efficiency and fast charging of EVs.

Table 1 shows the challenges of integrating the multiple renewable energy sources and energy storage devices with converters. As mentioned in Figure 1 the conventional multiple sources general architecture has multiple converters with separate control for each with simple control and extreme losses due to the inclusion of a greater number of switches [6]. The proposed multiple input (MI) converter, shown in Figure 2, reduces the losses by decreasing the number of redundant conversion stages and parallelly increasing the challenge in controller design [7]. Many reviewers said centralized control by connecting to a single converter offers better performance and reduced losses [8]–[15]. The MI converter's design and management should accomplish the behavior of sources.

The power electronic interfaces only decide the effective functioning of the EV to meet range and speed with optimized energy consumption. Converters are the heart of the system to perform well, they pump the necessary current based on the requirement, and the controller is the system's brain to have better control to protect all the devices and load. The choice of the converter is significantly based on the direction of the converter (unidirectional and bidirectional) and isolation (isolated and non-isolated). Specifically, the energy storage devices need bidirectional converters, and RES needs unidirectional converters [16] then high power handling circuits need galvanic isolation for safety. The non-isolated topologies are suitable for low-power systems less than 600 W, whereas isolated topologies are ideal for those greater than 600 W. In parallel, it stated that the non-isolated topology performs better and is cost-effective compared to the isolated topology. Based on control and power handling capacity, the isolated converter performs better than the non-isolated topology [17] for EV charging.

Table 1. Challenges of RES and ES integration

RES & ES combination	Objective	Remarks
Solar, wind	Utilize the complete RES without integrating with grid	- Impact on grid integration is greatly reduced - Proper energy management is needed
Solar, battery	Energy stored in battery at day time and utilized at night time.	- The energy is limited due to single source - Size of photovoltaics (PV) is high to supply the necessary demand
Solar, fuel cell, battery	To minimize the size and cost of the system.	- Overall energy is increased and the storage capacity can be reduced - Performance also improved
Solar, battery, supercapacitor	To support fast charging and to enhance the battery life span	- The peak power demand is supplied by the supercapacitor - Size of the battery is greatly reduced
Fuel cell, battery	To achieve unlimited energy level	- Proper design and protective system are needed - Power is limited due to single source

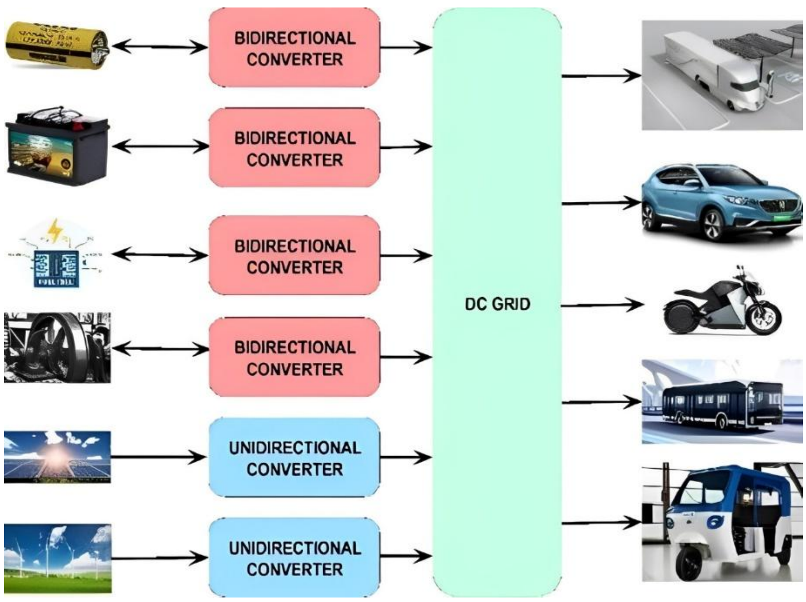


Figure 1. Conventional method of interfacing of multiple inputs with DC grid

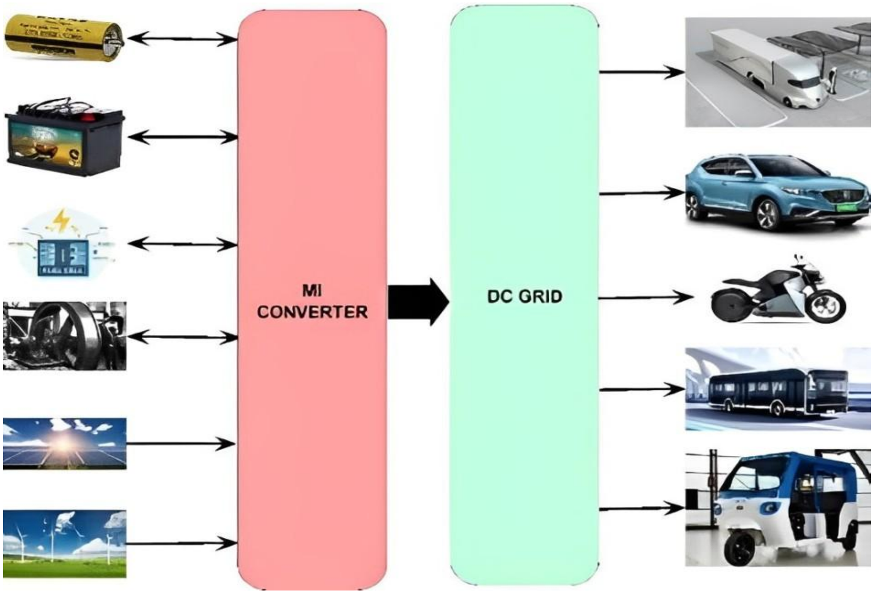


Figure 2. Multiple inputs interfaced using MI converter

MI converters can be classified based on magnetically coupled, electromagnetically connected, and electrically connected converters. The isolated bidirectional converters are coming under electromagnetically and magnetically linked. The voltage gains of the magnetically and electromagnetically connected MI converters depend on the transformer turns ratio and the duty ratio of the switches. Thus, the electromagnetically connected converter has the advantage of high voltage gain in contrast to the others [18]. The multiport isolated converters are clustered based on the transformer as two-winding transformer-coupled, multi-winding-transformer-coupled, and multi-transformer-coupled [19]. In two-winding transformers, the galvanic isolation between the input and output is established, not between all ports. In the multi-winding type, galvanic isolation is found between all converter ports. In the third type, the primary and secondary winding are coupled as dual active bridge types, and based on the requirement, the ports are connected using either a half-bridge or full bridge. Table 2 describes the comparison of MI converters.

Table 2. Comparison of MI converters

Topology	Gain	Zero current switching (ZCS)/Zero voltage switching (ZVS) switching	Number of components	Cost	Power density	Control complexity
Isolated	High	Critical	High	High	Medium	High
Non - isolated	Low	Critical	Less	Less	Low	Less
Electromagnetically coupled	High	Critical	Medium	Less	Medium	High
Magnetically coupled	Medium	Critical	High	High	Medium	Less
Electrically coupled	Low	Critical	Less	Less	Low	High
Modular	High	Critical	High	High	Medium	High
Non -modular	Low	Critical	Less	Less	Low	Less
Multi-input single - output	Low	Critical	Less	Less	Low	Less
Multi-input multi - output	High	Critical	High	Less	Medium	High
Resonant MI power converters	High	Easy to achieve	High	High	Very high	Less

MI DC-DC converters can be controlled by many control techniques like proportional integral derivate (PID), sliding mode control (SMC), model predictive control (MPC) [20], fuzzy [21], and artificial intelligent algorithms (AIA) [22]. The conventional PID method is suitable for linear control, but the remaining methods are ideal for nonlinear control. The multidevice interleaved bidirectional converter is mainly emphasized for high-power battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) for having less electromagnetic interference, shallow output voltage ripples and input current surges, high efficiency and reliability, bidirectionality, moderate cost, and compact size [23]. Even though many researchers extensively focused on MI converters of both unidirectional and bi-directional, this review paper intended to only focus on bi-directional MI converters with all terminologies related to them.

This review appraised the terminologies related to bi-directional MI converter in section 2 different bidirectional MI converter topologies are discussed, which mainly find their application in battery charging with the integration of RES and multiple storage devices. This section elaborately reviews the two categories of isolated and non-isolated MI converters for high and low-voltage applications. The summary based on a number of components, specifications, power and voltage gain is given in a table. The next section focuses on the future perspective and inferences from the review and is followed by the conclusion.

2. TOPOLOGIES OF MI CONVERTERS

Since this review focuses on bi-directional MI converters applicable for EV charging, the discussion is deeply on isolated and non-isolated MI converters. Usually, the non-isolated MI converters are developed from the buck and boost converters with compact size and high-power density. The isolated topologies are developed from bridge converters with a wide output range and soft switching. Many modulation approaches have been explored and developed to control the rising fields of MI DC-DC converters. Pulse-width modulation (PWM), frequency modulation (FM), and phase-shift modulation (PSM) are the common switching control approaches for switch-mode converters. Other than these, intelligent controllers have been implemented to optimize the PWM, FM, and PSM input. Due to its simplicity, PWM has been widely used in various applications to manage switching-mode power DC/DC converters to control either voltage or current. FM has been used for half-bridge isolated resonant converters, whereas PSM is used for full-bridge isolated converters [24], [25]. As per the EV charger stipulations, the levels are categorized as up to 3.7 kW is level 1, 3.7 - 22 kW is level 2 and above these is level 3. Then level 3 is divided into AC (22 to 43.5 kW) and DC (up to 200 kW), fast charging DC (above 200 kW). The specifications of the EV charger protocols are defined in different standards for different countries as SAE J1772 (USA), EN 61851 and IEC 62196 (Europe), JEVS G101 (Japan), GB/T 20234 (China). Recently, China, Germany and Japan jointly designed the EV charger ChaoJi has a power rating of 900 kW for ultra-fast charging.

2.1. Non-isolated-low voltage MI converter

The development of MI converters started with the combination of the basic DC-DC converters, which need proper design and control for applications [26]. The basic converters without energy buffers are buck and boost converters, and those with energy buffers are buck-boost [27], single-ended primary inductor converter or SEPIC [28], and Cuk and Zeta converters [29]. Figure shows the formation of a simple MI converter from a boost converter [30], using a simple voltage regulator to generate the control signals for switches through PWM to control the MI converter. An MI converter designed with bidirectional for multiple sources with PV, fuel cell or FC and battery needs optimized control for managing power between sources [31], [32]. The diode-capacitor voltage multiplier stages are cascaded in the output stage based on the design requirements to increase the output voltage. The independent source operation with different ratings must be integrated to improve the converter's flexibility. The circuit in Figure 4 was built by combining a buck with a boost converter, which can operate independent sources where the sources are operated individually.

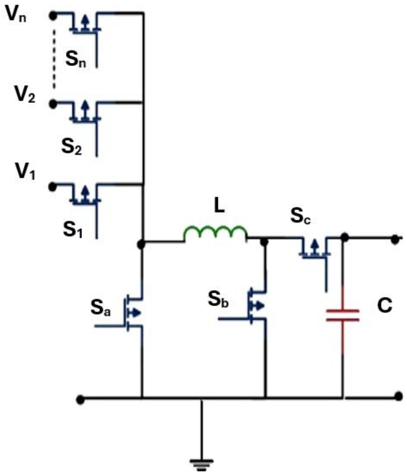


Figure 3. MI converter from boost converter [30]

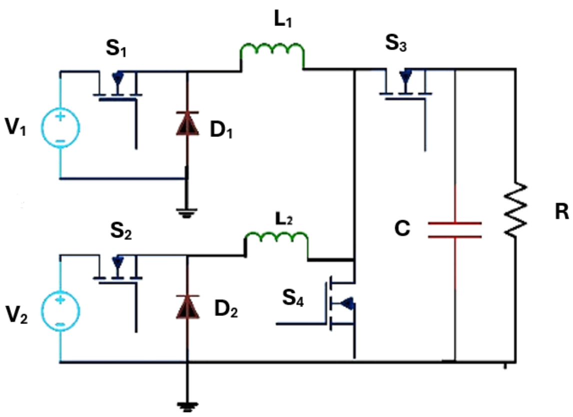


Figure 4. Buck and boost combined MI converter [27]

A back-to-back connected boost converter with PV, FC, and battery as sources with self-defined power management control gives a simple circuit for hybrid electric vehicle (HEV) [33]. The PV is the source when demand power is less than PV power, and when demand power is more than PV power, both FC and PV supply power, and when demand power exceeds the power, the battery adds to that. An MI converter with battery and ultra capacitor (UC) as source with both fuzzy and PI control achieved a better control based on voltage reference [34], [35]. If the output voltage is lower than the battery voltage, the battery is in discharging mode or regenerative mode. If the output voltage is less than the battery voltage and the power is less than the charging of super capacitor (SC). The smooth power profile is achieved with the improved battery life cycle.

In a new joint control approach for a three-level multiport converter is proposed with current and voltage control combined for controlling the battery and supercapacitor output using the bidirectional buck-boost converter shown in Figure 5 [36], [37]. Charge equalization is a big challenge when many batteries are interleaved through multiple converters. A consensus-based control achieves the three objectives of battery state of charge (SOC) equalization, proportional current sharing, and current regulation [38] to improve the battery life. For hybrid energy storage system or HESS, the life of the storage devices can be increased based on the charging and discharging level of the state of charge [39]. [40] proposed a simple boost converter-based multiport converter for multiple renewable sources integrated with battery-operated at high efficiency at 75 kHz switching frequency. Figure 6 is suitable for the combination of battery and SC, where multiple SCs can be combined based on the storm's rating. By predicting the inductor current using the forward Euler approach, the MPC algorithm-based converter finds the optimal duty ratio to regulate the output with a control and prediction horizon limit of one and less simulation time of 50μs [41]. A moving average filter method employed for current control and MPC with a move blocking technique for variable frequency control achieved 96% efficiency. The voltage regulation index and settling time were considerably reduced for the single inductor multiple port converter [42].

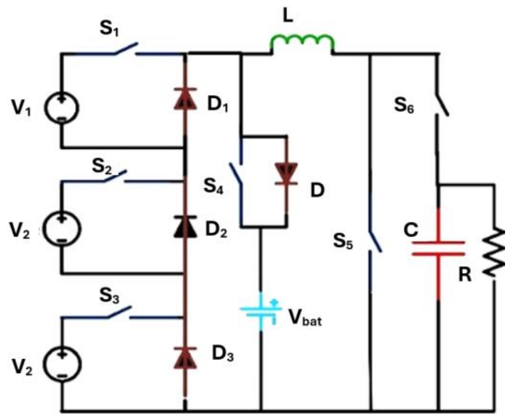


Figure 5. More than two buck inputs with boost converter [36]

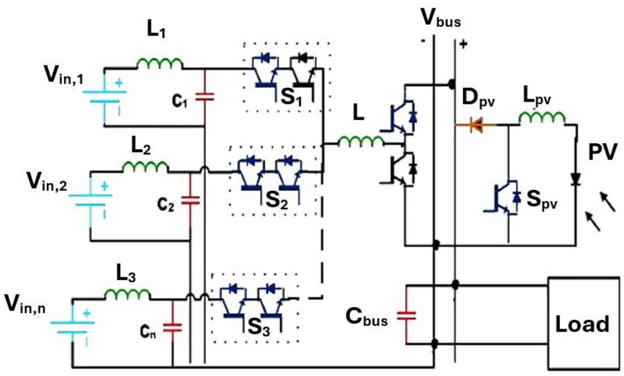


Figure 6. Three-level MI converter [40]

Figure 7 is a modified buck-boost converter with power and voltage as the control parameters, proving that efficiency deteriorates with a reduced number of switches [43]. The non-isolated MI converter can be designed for high-power applications as a modular structure [44]. The modular structure for a wide voltage range reduces the voltage and current stress on the switches and the efficient component utilization with less filtering requirements [45]. Figure 8 shows the three-level modular structured MI converter that suits high voltage levels. Modular multilevel triangular power-sharing establishes a wide voltage conversion ratio [46]. A simple dual-input converter with a bootstrap circuit with a charging switch makes the circuit less complex and easy to charge and discharge storage devices [47]. Figure 9 displays a simple inverter-modified structure with simple control and less stable.

The intelligent fuzzy controller performs better than the simple PI controller on an MI converter with a simple buck-based structure. To resolve the compatibility issue, the multi-input multi-output or MIMO converters were developed with a single inductor for multiple inputs and multiple outputs by taking the inductor current as a control parameter [48], [49]. Even though a single inductor constant current MIMO converter achieves less efficiency, there is no compromise in cross-regulation and scalability [50]. The reconfigurable structure based on the requirement of the number of inputs and outputs is more flexible for the construction of an MI converter [51] shown in Figure 10. The capacitor-based MIMO converter is suitable for mobile applications that are more compact and lightweight. The adaptive tuning method for different operating modes improves the converter's efficiency compared to the fixed reference method [52]. By employing a resonant tank, the non-isolated converter performs better by reducing losses due to ZVS and ZCS implementation [53]. Table 3 (see Appendix) [54]-[58] summarizes the non-isolated MI converter's components, control topologies, merits, and demerits.

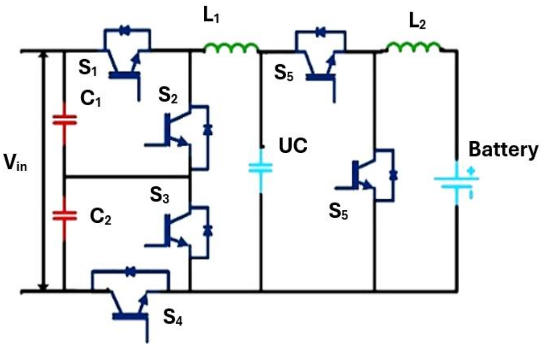


Figure 7. Modified buck-boost converter [43]

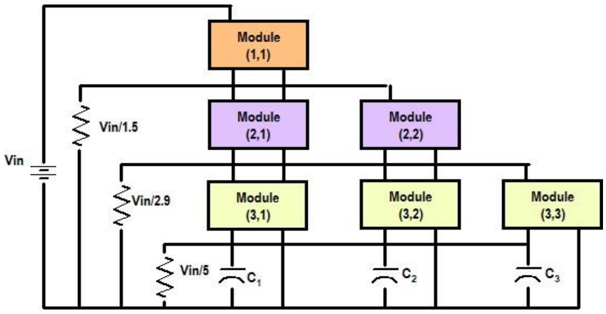


Figure 8. Modular structure of MI converter [46]

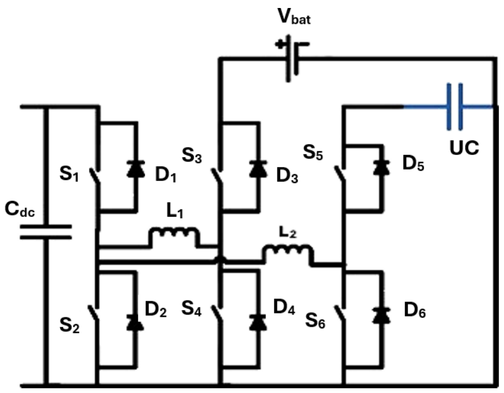


Figure 9. Modified inverter model [48]

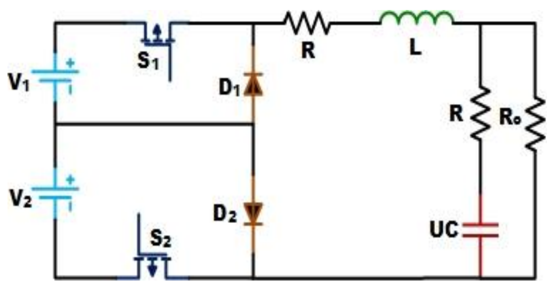


Figure 10. Simple buck-based MI converter [51]

2.2. Isolated–medium and high voltage MI converter

The Isolated MI converters are usually preferred for medium to high-voltage applications for safety and smooth control. The isolated MI converters are developed by combining the primary converters, like full bridge and half bridge converters, with high-frequency transformers or resonant tanks [59], which increases the losses and control complexity due to the increased number of switches. Still, the ZCS and ZVS operations can be achieved. In bidirectional isolated DC-DC converters, the series resonant dual stage resonant circuit performs with better efficiency [60]. The coupled inductor method helps to achieve voltage clamping and soft switching with isolation for multiple inputs or outputs [61].

Figure 11 shows the extension of dual active bridge for high power handling without affecting the component size leads to multiple ports interleaved by using a transformer, increasing the control and modelling complexity [57]. Furthermore, a degree of freedom is also added for modulation, which simplifies the system modeling and control, The converter should operate in discontinuous conduction mode to achieve better cross-regulation to mitigate the current stress and deteriorating the conduction loss. In continuous conduction mode operation, the dynamic changes of the loads disturb the other loads when connected with multiple output converters. In isolated modular MI converters in primary, the modules are connected as input series output parallel to reduce the output side's current stress during light load conditions [62]. The dual active bridge is used for conversion where the input and output sources are isolated by transformer winding with the turns ratio of 1:n [63]. The input sources are connected using two switches with anti-parallel diodes in parallel and series through the DC link capacitor.

Depending on the load demand, the sources may be the same voltage or voltages and can be operated in independent mode or combinational mode. The dual phase shift control is employed to control the inner and outer loop duty ratios, d_1 and d_2, of the rectifier and inverter, respectively by satisfying the condition $0<d_1<d_2<1$ and $0<d_2<d_1<1$. The maximum power has been attained when d_1 is 0 and d_2 is 0.5 to achieve the wide power control range. The decoupled PI controller improves the response time and reduces maximum overshoot [64]. The high-frequency transformer integrating a resonant tank helps reduce the size with no compromise in power density and efficiency. It gives a better solution for medium and high-voltage applications. Model predictive algorithm for MI bidirectional converter helps reduce the maximum overshoot and settling time for charging EVs with high reliability and efficiency [65].

Researchers have achieved multiple ports with multi-winding high-frequency transformers for isolated converters. Figure 12 is a three-port converter whose efficiency is high and suitable for both light load and full load conditions due to reduced stress. The inductor on the transformer side should be high enough to operate under a high switching frequency for better switching performance. The inductor on the DC load side inductor should be sufficient for high-power applications with lower output voltage [66]. The constant frequency control isolated bidirectional converter with constant gain and hybrid switching increases the power density of the converter [67]. The modular structure MI converter for high voltage applications needs an optimized controller for controlling the power flow; the structure is shown in Figure 13. The decoupling control suits many applications, allowing separate control for each port and making the controller design simple [68]. The PWM and phase shift hybrid control with synchronous rectification decreases the loss, and the output regulation is effective [69]. The digital controller smooths the transition and enhances stability. A few isolated MI converters are compared, and the detailed study is elaborated in Table 4.

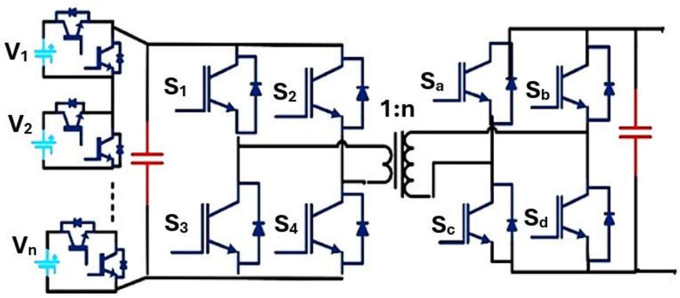
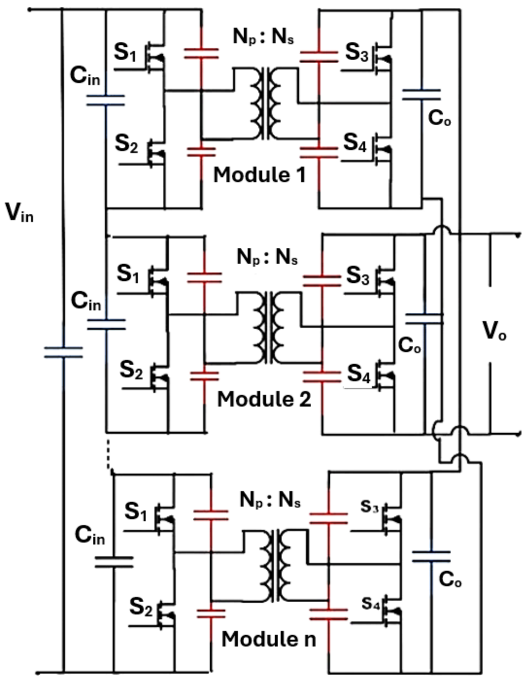


Figure 11. Dual active bridge MI converter [57]



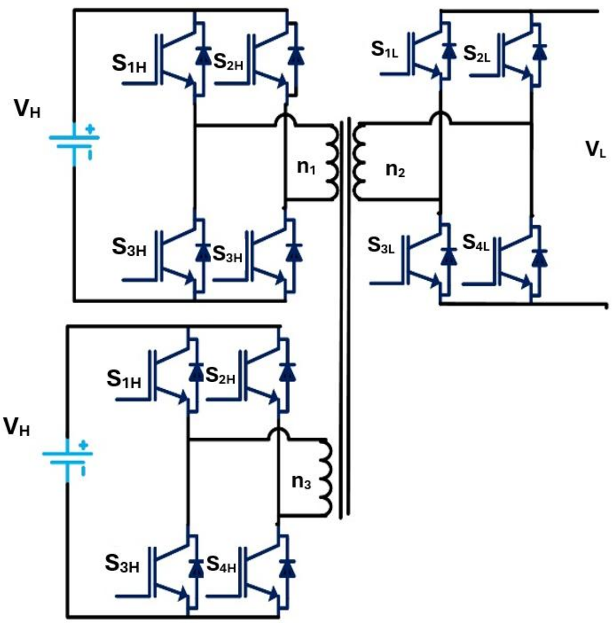


Figure 12. Three port converters [66]

Figure 13. Modular MI converter [69]

Table 4. Comparative study of isolated MI converters

Ref/ inputs	Type of converter	Specifications*		Control	Advantages	Remarks	Voltage/ power equation
[63] Multiple energy storage	Dual active bridge	Sw L N P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	12 1 1:10 200k 240 3.3k 20 NA 97	Dual phase shift	Reduce current stress High efficiency Easily expandable for extra power transmission	- The chance of imbalance when multiple batteries are connected - Optimal scheduling algorithm necessary for battery lifecycle improvement	$For\ 0 \leq d_2 < d_1 < 1$ $P = \frac{nV_{in}V_x}{2f_sL}\left[\left(d_2(1-d_2) - \frac{1}{2}d_1^2\right)\right]$ $For\ 0 \leq d_1 \leq d_2 < 1$ $P = \frac{nV_{in}V_x}{2f_sL}\left[\left(d_2(1-d_1 - \frac{1}{2}d_2\right)\right]$
[70] PV, wind	Current fed - resonant tank	Sw L N P IV OV SF(kHz) RF(kHz) η (%)	2 1 1:3 1k 48 310 150 200 93	Variable Frequency control	ZCS operation Less number of switches Less loss Suitable for different type of sources	- At minimum load efficiency very low - Voltage stress across the switches high under minimum load	$\frac{V_{dc}}{V_1} = \frac{\left(1+\frac{V_2}{V_1}\right)n}{(1-2f_s(T_{54}+T_{43}+T_{32}+T_{21})}$
[71] Multiple sources	Multi element resonant	Sw L N P IV OV SF(kHz) RF(kHz) η (%)	12 5 4:5:1 750 92,115 230 95 110 96.3	PWM and phase shift decoupling	Response time and maximum overshoot is considerably reduced Smooth power sharing is achieved	- Poor response for dynamic changes of load - Battery SOC not taken into consideration Σ	$V_p = j\omega L_k\left(n_{(p-1)p}i_{L(p-1)} + \cdots + n_{1p}i_{L1}\right) + \frac{4}{\pi}V\_T_p$
[64] Battery, FC	Triple port active bridge	Sw L N P IV OV SF(kHz) RF(kHz) η (%)	12 4 2:1:4 1k 56,30 220 25 NA 94.5	PWM and phase shift decoupling	Response time and maximum overshoot is considerably reduced Smooth power sharing is achieved	- Poor response for dynamic changes of load - Battery SOC not taken into consideration	$P_x = \sum_{n=1}^{\infty}\frac{V'_{xn}V_{(x-1)n}sin(\theta_{xn})}{(2n-1)X_L} + \cdots + V'_{xn}V_{(x+1)n}sin(\theta_{xn} - \theta_{(x+1)n})$
[72] Fuel cell, battery, SC	Three port active bridge	Sw L N P IV OV SF(kHz) RF(kHz) η (%)	12 5:1:5 400 60,13 60 20 NA 95	Phase shift and PWM	Suitable for wide range of voltage applications Conduction losses are high ZVS achieved	- Switching losses are high at light load efficiency is less - Better optimization algorithm needed for optimal load sharing during dynamic load change	$V_x^n = \frac{V_{sc}^n}{\frac{\left(1-\frac{\lambda_1}{M_0}\right)M_{1,3}}{M_0}}$
[69] PV, battery	Interleaved buck boost and full bridge	Sw L N P IV OV SF(kHz) RF(kHz) η (%)	4 3 1:2 100 28 12 100 NA 90	PWM and Phase angle shift	High power density ZVS achieved under some load condition	- ZVS not achieved during battery charging - Primary switch conduction loss is high	$V_o = V_{bat}\frac{d_{S1}}{1-d_{T0}} = V_{uc}\frac{d_{S1}}{1-d_{T0}}$ $V_o = \frac{V_{uc}}{d_{Q0}}$ $V_o = V_{bat}\frac{d_{S1}}{1-d_{T0}} = V_{uc}\frac{1}{1-d_{T0}}$
[73] PV, battery	Modified half bridge	Sw L N P IV OV SF(kHz) RF(kHz) η (%)	5 1 1:2 200 60 28 500 NA 92	Digital control	Centralized control Smooth transition between states	- Controller design is little complicated - Control loop decoupling is necessary	$V_o = \frac{(1+D')}{(1-D')}\left[\frac{1}{1-D}V_{pv}\right]$ $I_o = \frac{(1-D')}{(1+D')}[(1-D)I_{pv}]$

*Sw-Number of switches, L- Number of inductors, N-Turns ratio, P-power, IV- Input voltage, OV-Output voltage, SF-Switching frequency, RF-Resonant frequency, η -Efficieny

3. FUTURE SCOPE AND INFERENCES

From the discussions came to know that the future of vehicle charging converters will rely on resonant converters that operate under high power density and efficiency with a reduced operating frequency range. To achieve ZVS, a resonant tank is added to the on-board charger between the full-bridge rectifier and isolated phase-shift controlled full-bridge converter with fixed frequency control, achieving 97% efficiency, which is 7% higher than the hard switching charger. CLLC resonant converter with an asymmetrical design is suitable for vehicle charging applications due to the different forward and reverse voltage gains. When comparing half-bridge and full-bridge CLLC converters, the half-bridge performs better in efficiency and cost. Most common among the control techniques, the PWM is employed by generating switching signals based on the duty ratio depending on the small signal-averaged model and frequency domain analysis to improve the performance for small disturbances. An intelligent controller has been used to improve the transient and robustness of the large-signal stability analysis.

This implies that only one source can be utilized at a time to meet the load demand. The other limitations are zero voltage clamp, voltage range, and complex voltage regulation based on the topology. The future scope of MI converters is the development with reduced size, cost, and both DC and AC output with the best control of sources with high efficiency and voltage range. The future of power electronics depends on SiC [74], Ga_2O_3 and Ga_2O_3 [75] ultra-wide bandgap semiconductor switches, which replace the Si switches with increased bandwidth, high switching speed, and high-power handling capacity. The remarkable properties of these devices are faster switching speed, lower on-resistance, lower reverse recovery loss, lower parasitic parameters, and suitable for high operating frequency occasions. The implementation of hybrid control like machine learning with MPC and artificial intelligence-based converters are the future perspectives to make smart converters to enhance the good energy management of multiple sources.

4. CONCLUSION

With reduced complexity and easy implementation, the MI converter reduces costs and losses. The future research focuses on MI converter which provides both AC and DC at the output suitable for both on-board and off-board chargers. The non-isolated MI converter limits its voltage range, whereas the isolated MI converter with increased freedom allows the system to operate more flexibly and reliably. The DAB converter plays a significant role in bidirectional operation for high-power applications. The main concern is reducing the system's size, loss, and cost by introducing the resonant tank that operates under high frequency. The various resonant circuit combinations find different applications based on their natural characteristics. In the resonant tank, the series and parallel LC resonant circuit perform better for vehicle applications where both series and parallel LC characteristics are combined. In wireless charging, the isolated MI converter with a resonant tank may also find its applications for increasing efficiency and achieving fast charging. So, future research is developing an MI resonant converter to avoid the MI -DAB converter shortcomings with compact size and wide voltage range. Based on the review, the development of MI MI-based resonant converter is suggested for EV applications for high power density and high efficiency. The major challenge is to raise its optimal control of input and output voltages with the increased power density and voltage range, which supports battery charging and fast charging. From various perspectives, MI bidirectional converters have been investigated specifically for EV applications. The MI converter has applications in EV and renewable energy nowadays and many industrial applications like telecommunications and satellites.

APPENDIX

Table 3. Comparative study of non-isolated MI converters

Input sources	Type of converter	Specifications*		Control	Advantages	Remarks	Voltage gain/cost function
[54] Multiple sources	Switched resonant converters	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	I+O I+O 1 200 240 150 250 116k 93.5	Route matrix method	· No transformer used · ZCS operation achieved	- Connected with forward-conducting bidirectional-blocking switch - Capable of arbitrary power routing	$\frac{V_o}{V_i} = \sqrt{2RC_r f\_s}$ $f_{pr} = \frac{1}{2\pi\sqrt{L_{r0}C_r}} = \frac{\omega_r}{2\pi}$ $Z_r = \sqrt{L_{r0}C_r}$

Table 3. Comparative study of non-isolated MI converters (continued)

Input sources	Type of converter	Specifications*		Control	Advantages	Remarks	Voltage gain/cost function
[55] 3 Battery/3 SC	Buck boost	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	I+1 1 1 110 230 110 10 NA 97	PWM, Fuzzy	Sources with different voltage levels can be integrated Effective control of source based on their energy level	- Works well even in the absence of one source - Decoupled current and voltage controller employed	For unequal voltage source, $V_o = \frac{V_1 d_1 + V_2 d_2 + V_3 d_3}{1 - d_3}$ For equal voltage source, $V_o = \frac{3Vd}{1-d}$
[30] PV, battery	Buck TPC	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	3 1 3 35 30 5 20k NA 89	Voltage regulator, PWM	Minimum number of magnetic components Compact in size Simple and easy to implement	- No soft switching available - Suitable for integrating RES and storage devices	$V_o = D_1 V_{in} + (D_2 - D_1) V_b$
[31] 3I PV, FC, battery	Buck and boost	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	6 2 5 8.3k 80 210 25k NA 91	PWM	Both unidirectional and bidirectional ports available Suitable for high voltage applications	- Number of switches, diodes and capacitors are more - High switching losses - No ZCS operation	$V_o = \frac{(1+D')}{(1-D')}\left[\frac{1}{1-D} V_{pv}\right]$ $I_o = \frac{(1-D')}{(1+D')}[(1-D) I_{pv}]$
[32] 3I PV, FC, battery	Buck-boost and boost	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	4 2 2 152 35 280 30 NA 92	PWM	Multiple sources can be active Combination of unidirectional and bidirectional power flow	- No ZVS and ZCS operation - Losses high - Hard switching	$M = \frac{(1 + D^2 - D)}{(1 - D)^2}$
[33] 3I PV, FC, Battery	Boost	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	4 2 2 80 20 110 30k NA 86	PI, PWM	Reduced losses Individual sources can be operated Voltage stress is high during maximum load	- ZVS and ZCS operation not achieved - Efficiency is low at max load	$V_o = [(d_3 - d_2)(V_{FC} + d_1 V_{batt} - r_2 i_{L_2}) + (1 - d_3)(V_{pv} + d_1 V_{batt} - r_1 i_{L_1})]/(1 - d_3)(d_1 - d_2)$
[34] 2I Battey SC	Buck and bidirectional converters	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	5 2 2 3k 120 120 20k NA 92	Fuzzy and PI	Proved that the battery life cycle has been improved Bidirectional operation can be achieved smoothly	- ZVS and ZCS not achieved so switching losses high - Current stress is high at minimum load	$V_o = V_{bat} \frac{d_{s1}}{1 - d_{T0}} = V_{uc} \frac{d_{s1}}{1 - d_{T0}}$ $V_o = V_{bat} \frac{d_{s1}}{1 - d_{T0}} = V_{uc} \frac{1}{1 - d_{T0}}$
[56] 2I Battery, SC	Buck-boost/buck	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) η (%)	4 2 1 1k 36 48 20k NA 93	PI	Applicable for low power applications Reduced losses due to less no of switches High efficiency	- Efficiency is higher for charging mode than discharging mode - ZVS and ZCS not achieved so switching losses high	$V_o = V_1 \frac{d_{s1}}{1 - d_{T0}} = V_2 \frac{d_{s2}}{1 - d_{T0}}$

Table 3. Comparative study of non-isolated MI converters (continued)

Input sources	Type of converter	Specifications*		Control	Advantages	Remarks	Voltage gain/cost function
[42] PV, Multiple battery	Single inductor Multiple port	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) ɳ (%)	2I+3 I+2 I+1 200 50 80 10k NA 96	MPC	– Less no of components – Less control complexity – Execution time is 35μs which is less	– Switching loss is high due to hard switching – Not suitable for higher rating	$J = \sum_{j=1}^{N_c} [v_{Ref} - v_{Bus}(k + j)]^2$
[57] Battery, SC	Modified inverter model	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) ɳ (%)	6 2 1 5k 144 300 20k NA 94	PWM	– Sources can be independently operated – Less control complexity – Less components	– ZVS and ZCS not achievable. – Operation under light load reduce efficiency	$M_1 = \frac{V_{Bt}}{V_{dc}} = \frac{1-d_2}{d_1}$ $M_1 = \frac{V_{UC}}{V_{dc}} = \frac{1-d_2}{d_2}$
[58] Solar, battery	Double input buck	Sw L C P(W) IV(V) OV(V) SF(kHz) RF(kHz) ɳ (%)	2 1 1 800 220 180 100k NA 92	One cycle controller	– Less loss due to less components – Easy to control	– Not suitable for high power applications – Conduction Losses are more	$V_o = \left[\frac{(1-d_1+d_2)}{d_2(1-d_1)}\right]V_{g_2} - \left[\frac{(1-d_2)}{d_2(1-d_1)}\right]V_{g_1}$

*Sw-Number of switches, L- Number of inductors, N-Turns ratio, P-power, IV- Input voltage, OV-Output voltage, SF-Switching frequency, RF-Resonant frequency, ɳ -Efficiency

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